HEV's: Here and Now TOPTEC

Trading off HEV Fuel Economy and Emissions through Optimization

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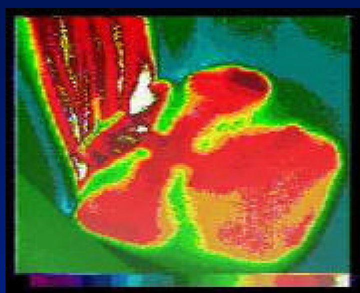
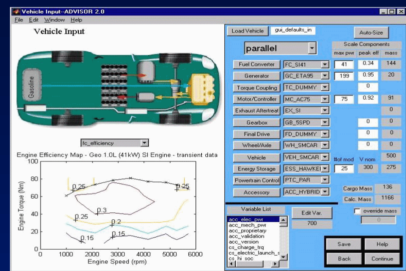
Acknowledgements

- NREL: Keith Wipke, Valerie Johnson, Tony Markel, Sam Sprik,Terry Penney
- VR&D: John Garcelon

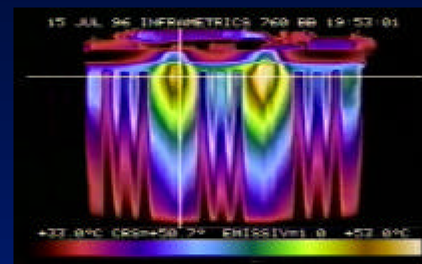
DOE Hybrid Electric Vehicle Program



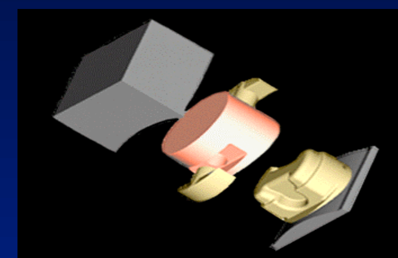
Vehicle Climate Control



Vehicle Systems Analysis

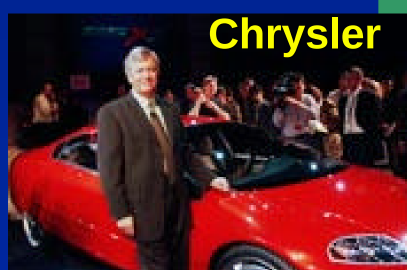


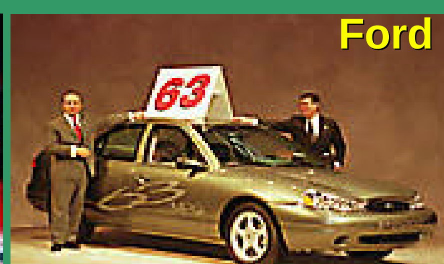
Battery Thermal Management

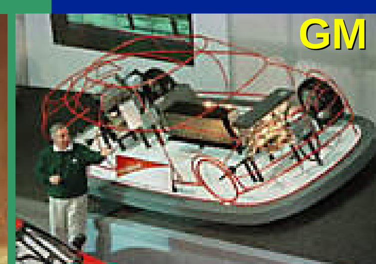


Vehicle Systems Virtual Prototyping

Big 3 Partnership
(55 mpg, mid-size vehicle)







Outline

- Background
- Vehicle Design Tradeoffs
- Vehicle Control-Strategy Tradeoffs
- Effect of Drive Cycle
- Conclusions/Current Activities

Background

- Push for higher fuel economy: CAFE, global warming
- Push for lower emissions: EPA Tier 2, CARB LEV-II
- Some efforts help both: reduced mass, aero drag, rolling resistance, and auxiliary loads
- For conventional vehicles, tradeoffs include:
  - CI vs SI engine (better MPG, worse NOx & PM)
  - Engine "tuning" (timing, A/F ratio, etc.)
  - Use of EGR (better NOx, slightly worse MPG)
- HEVs provide additional optimization potential

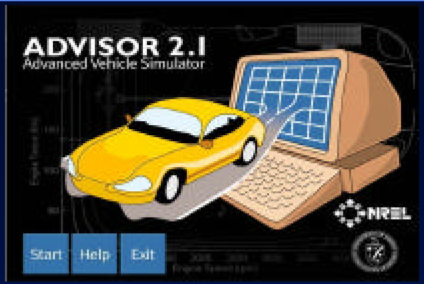
Approach for HEV Tradeoff Study

- Select vehicle, drive cycle, and performance objectives
- Model vehicle behavior (fuel use and emissions)
- Predict the effect of different design and control options
- Perform multi-dimensional optimization on key options
- Check applicability to other vehicle and cycle types

Baseline Vehicle Configuration

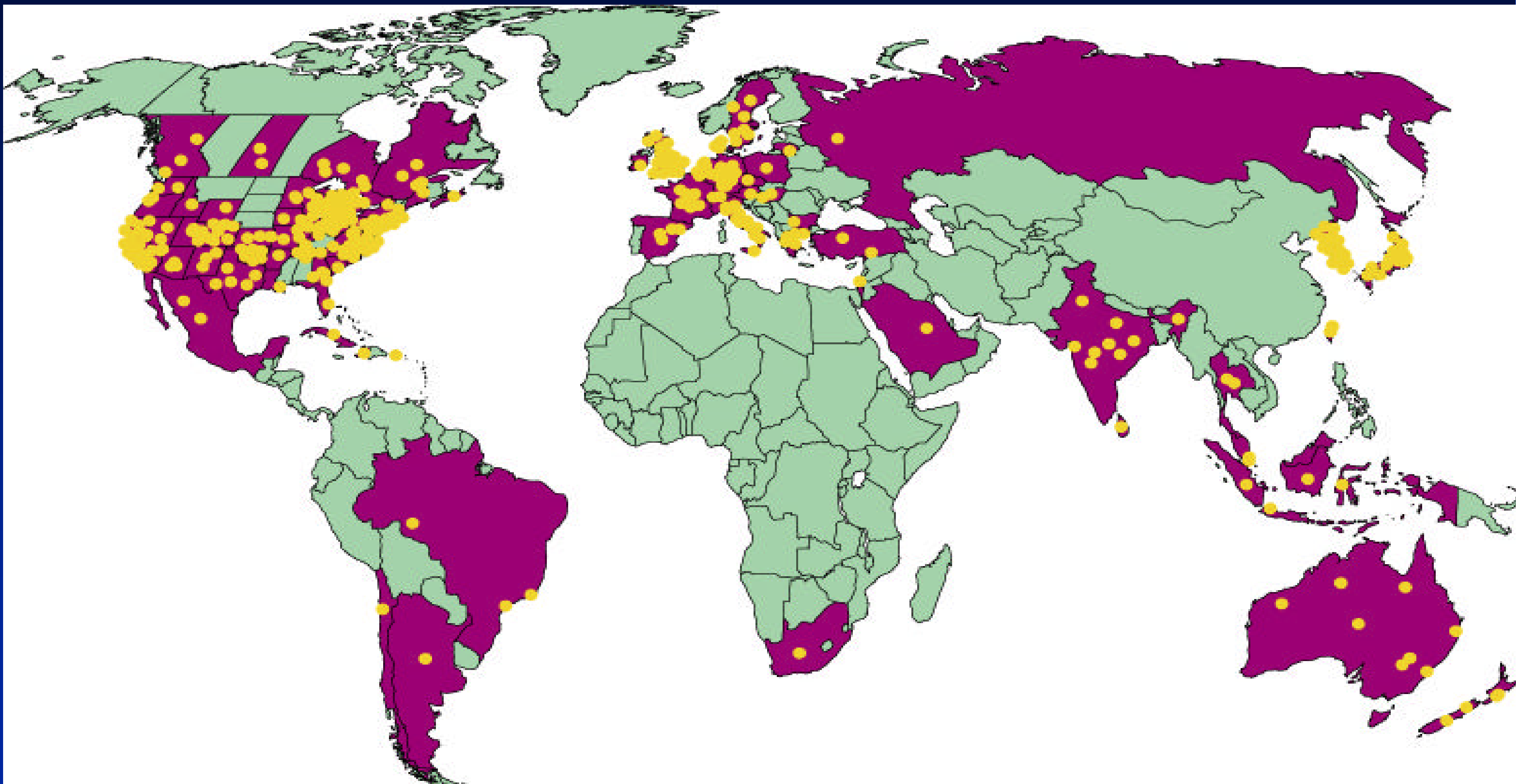
- Vehicle: "PNGV-type" mid-sized 4-door ($A_f = 2\ m^2$)
  - Reduced "glider mass" (500 vs ~900 kg), aero drag (0.20 vs ~0.33), rolling resistance (0.007 vs ~0.009), & auxiliary loads (700 vs ~1000 W)
- Required vehicle performance: Gradability: 6.5%, acceleration: 0-60 mph in 12s, 40-60 mph in 5.3 s
- Fuel economy evaluated on US EPA city/hwy cycles, emissions evaluated on US EPA city cycle (FTP-75)
- Conventional, series (power follower), & parallel with:
  - Base engine: 1.9 l VW TDI
  - Advanced high-power lead-acid batteries (in series and parallel)
  - All components scaled (mass and peak power) to deliver equal performance

Background on ADVISOR



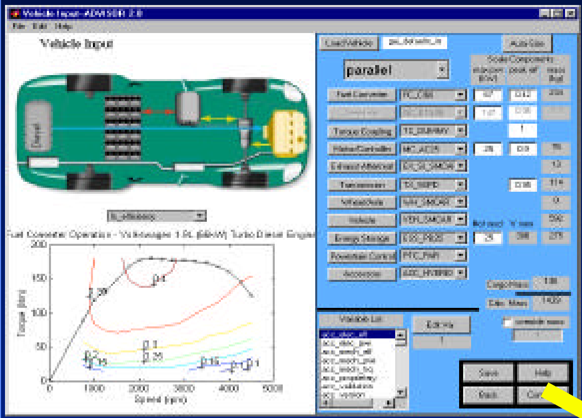
- ADVISOR = ADvanced VehIcle SimulatOR
  - simulates conventional, electric, or hybrid vehicles (series, parallel, or fuel cell)
- Created in ‘94 to support DOE HEV Program at NREL
- Freely distributed via: www.ctts.nrel.gov/analysis
  - Current version (2.1.1) released on web 4/13/99
  - Users provide component data and validation

ADVISOR Being Used Globally
May 1999: ~600 users

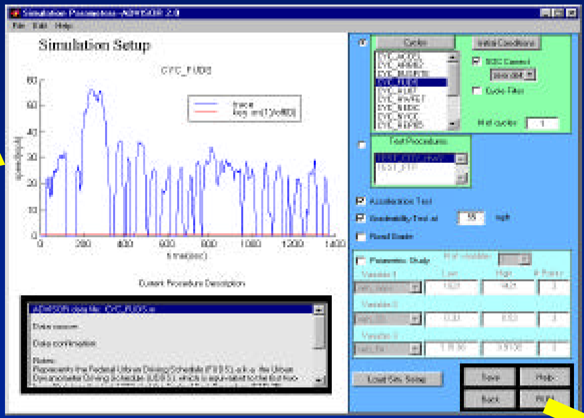


Three Main ADVISOR Screens

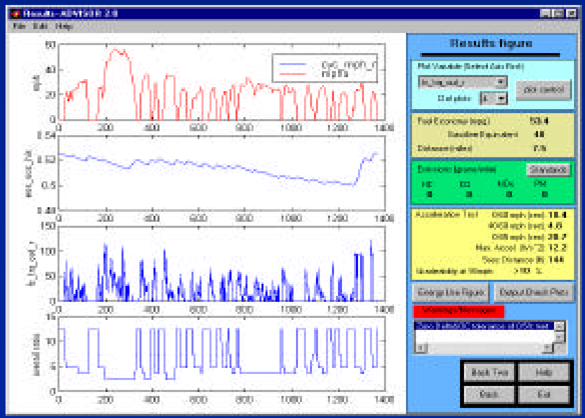
Vehicle Input



Simulation Setup

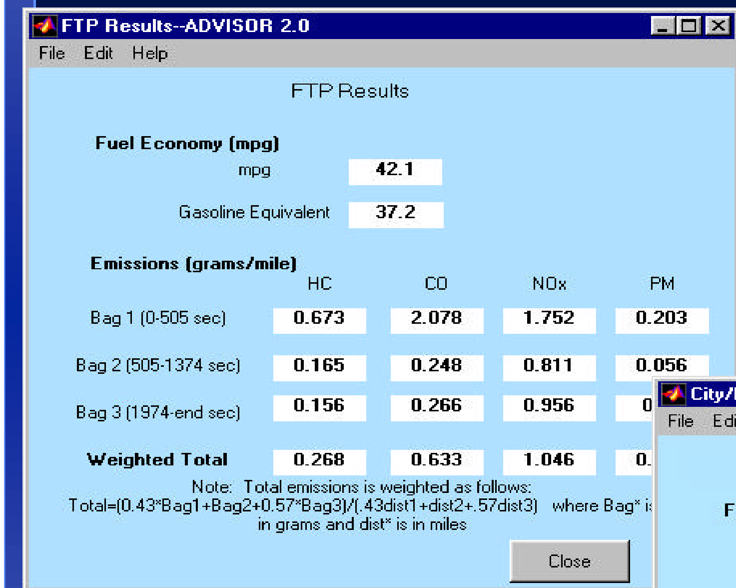


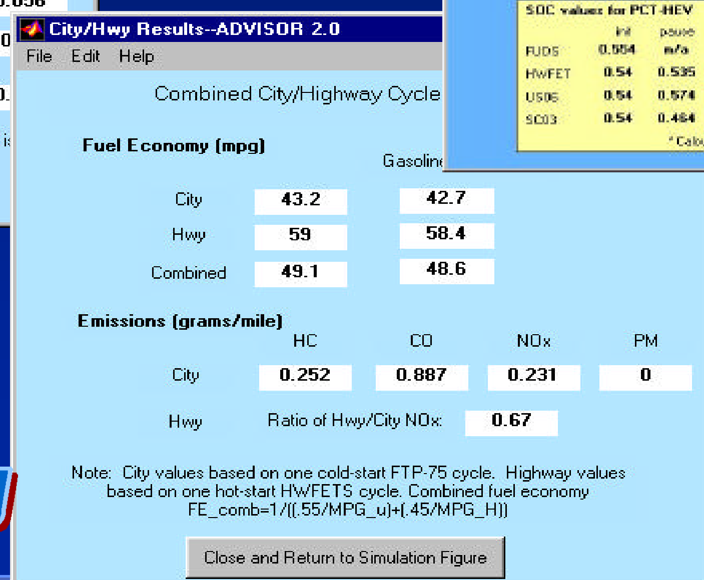
Results

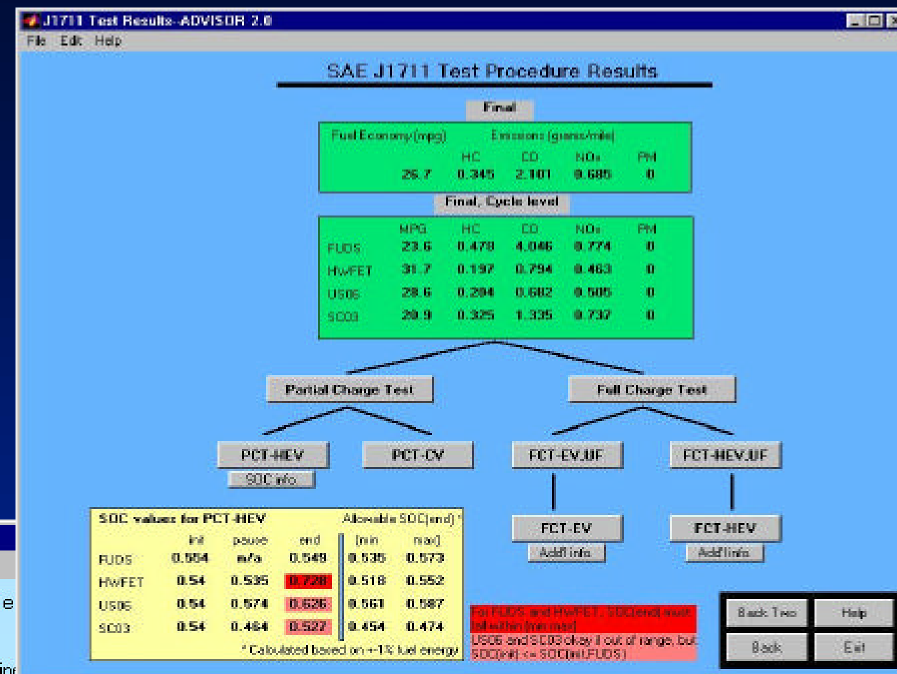


ADVISOR Test Procedures Available

FTP Test



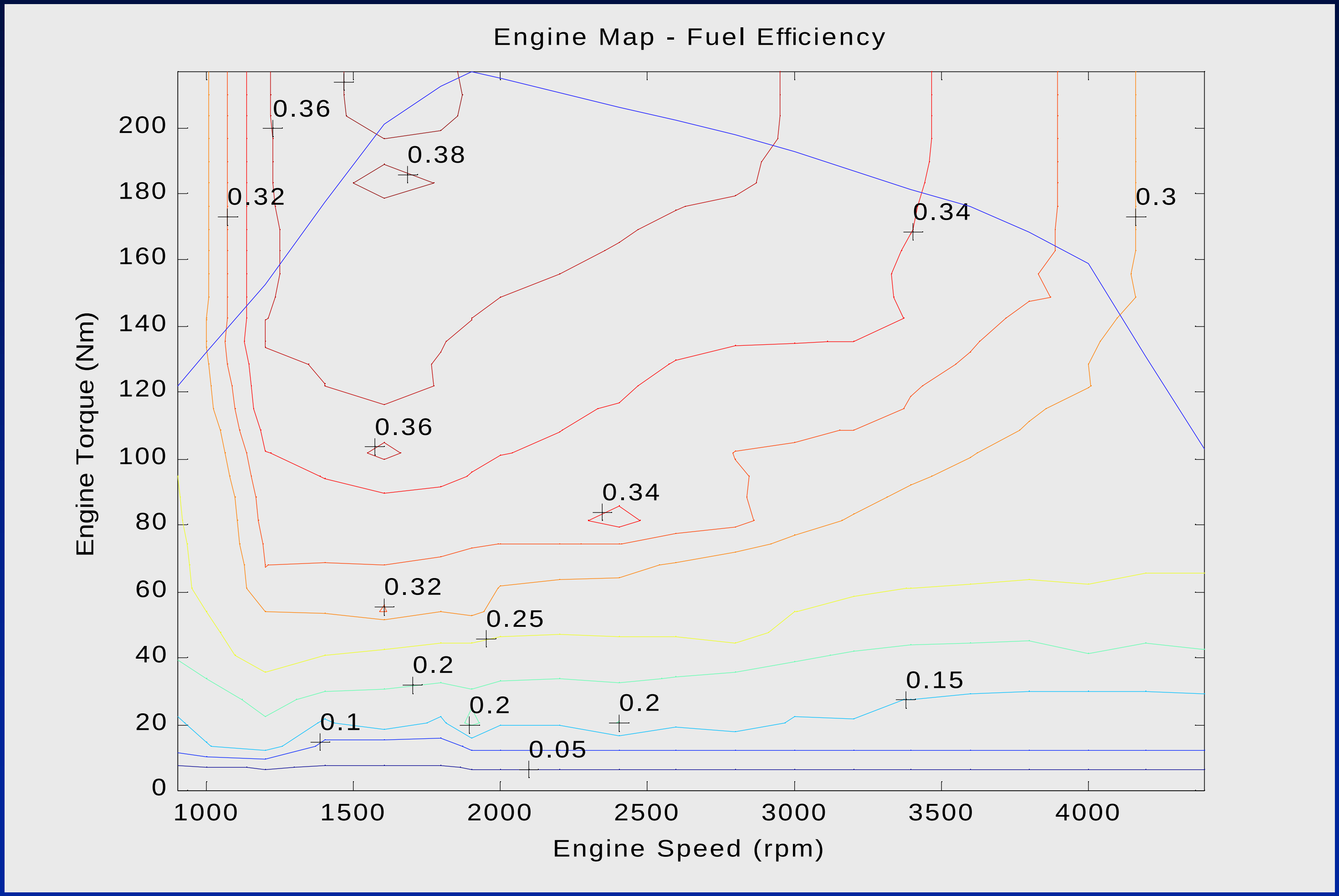




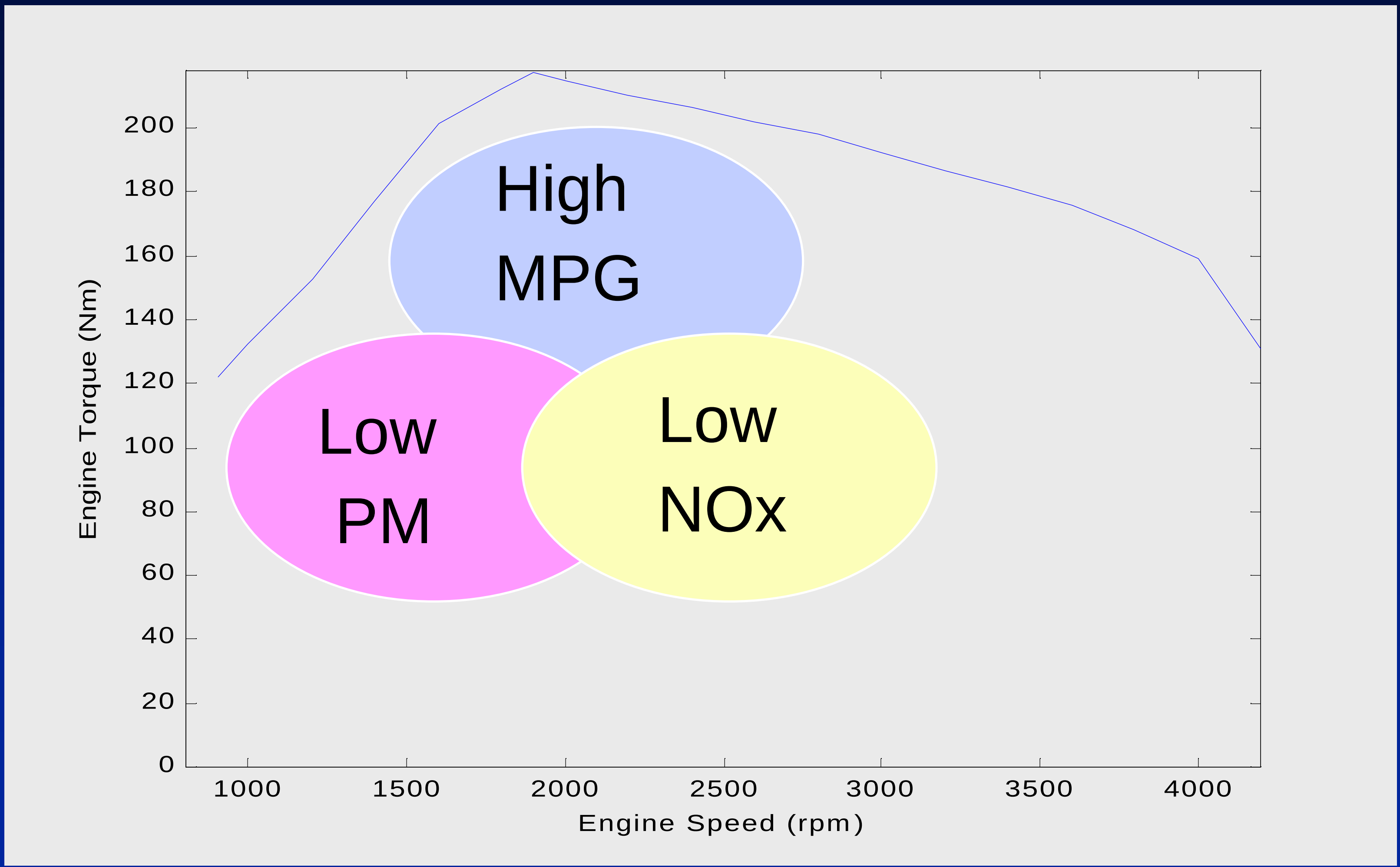
SAE J1711 HEV Test Procedure

Combined City/Highway

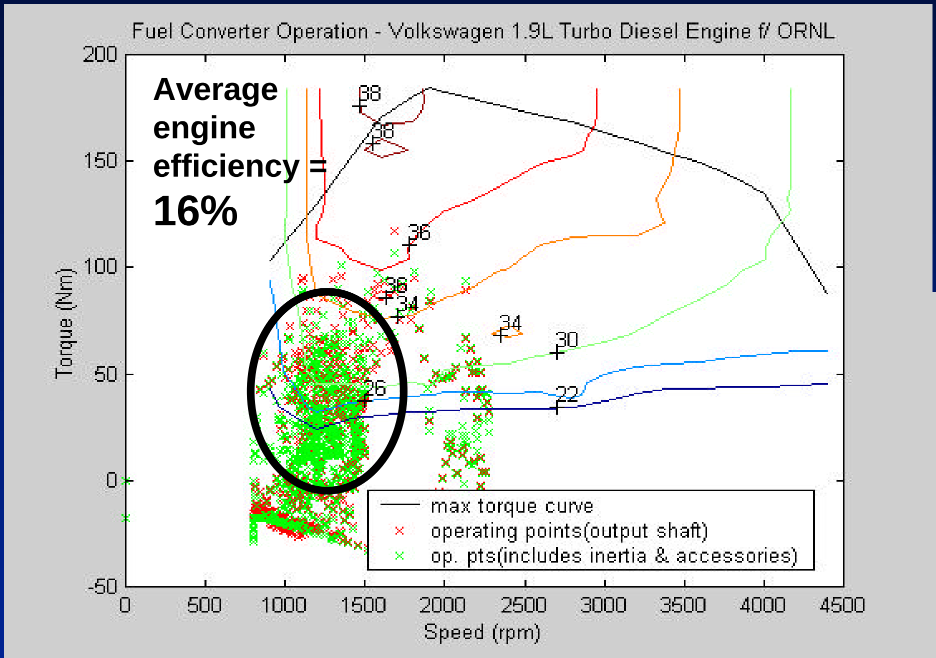
Efficiency map for CIDI engine

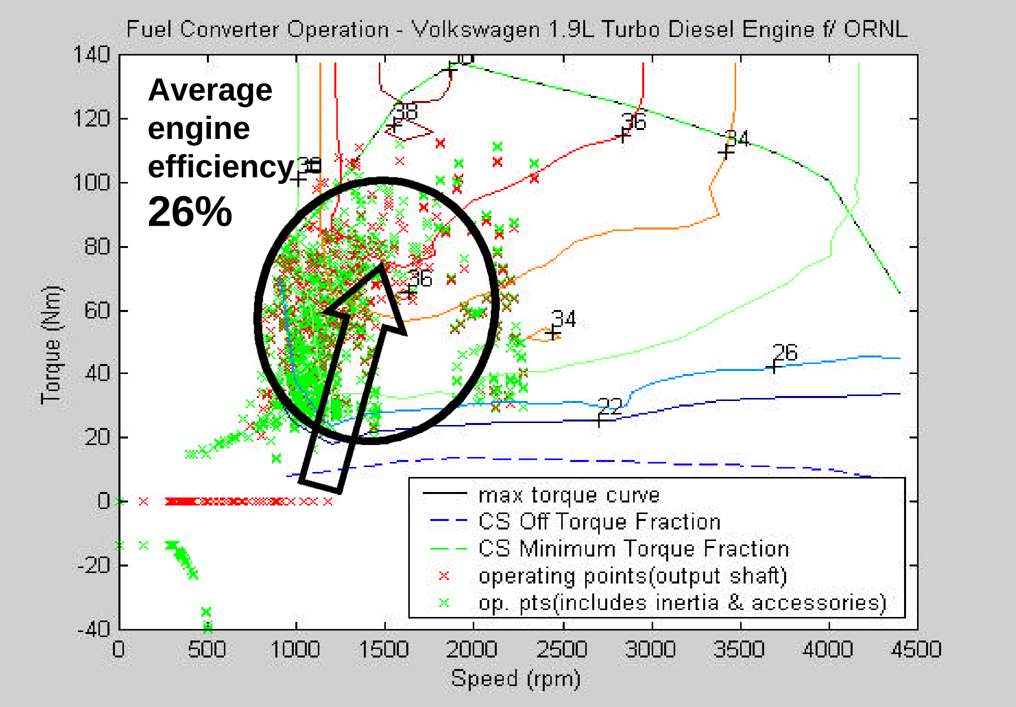


For this CIDI engine, different regions provide different benefits

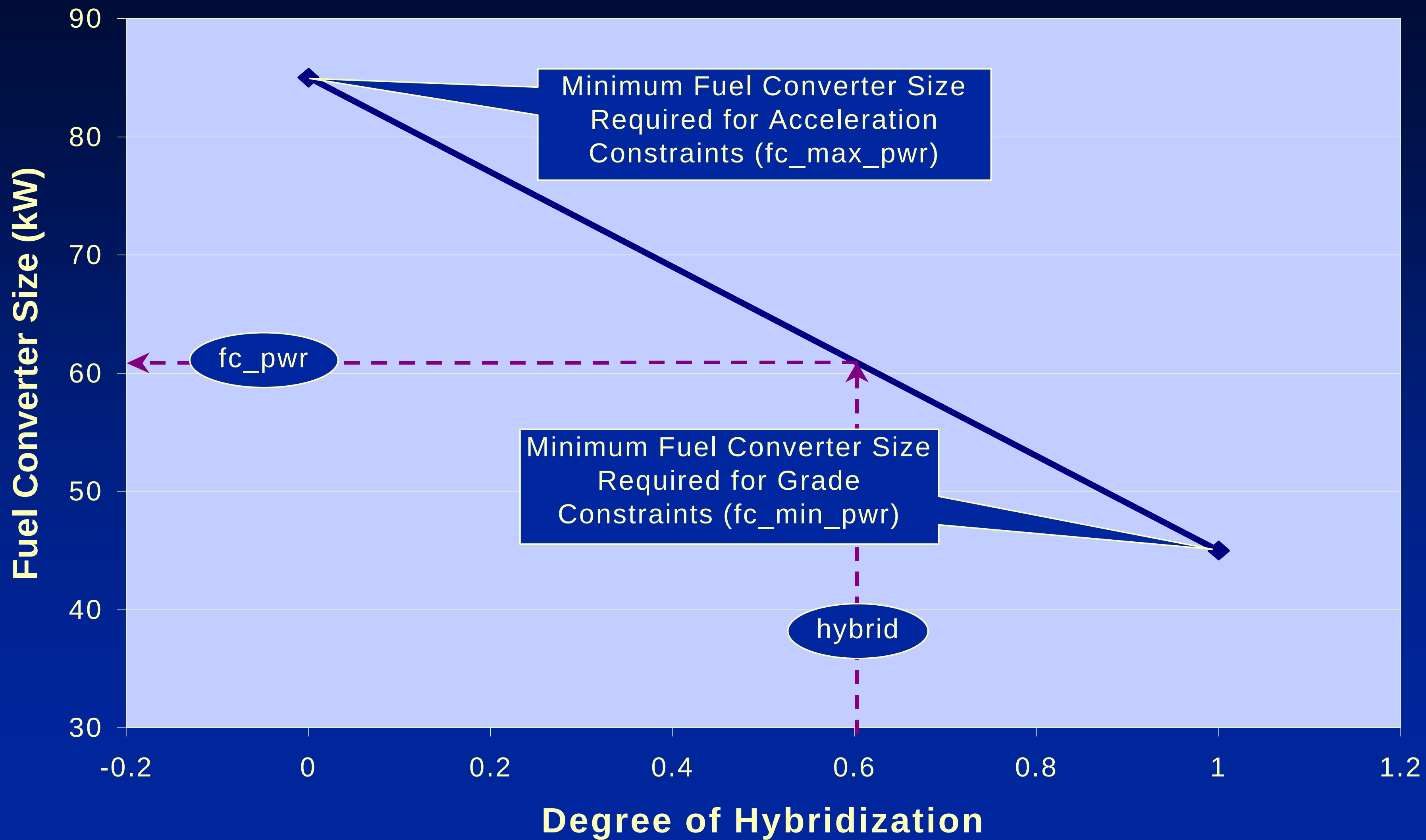


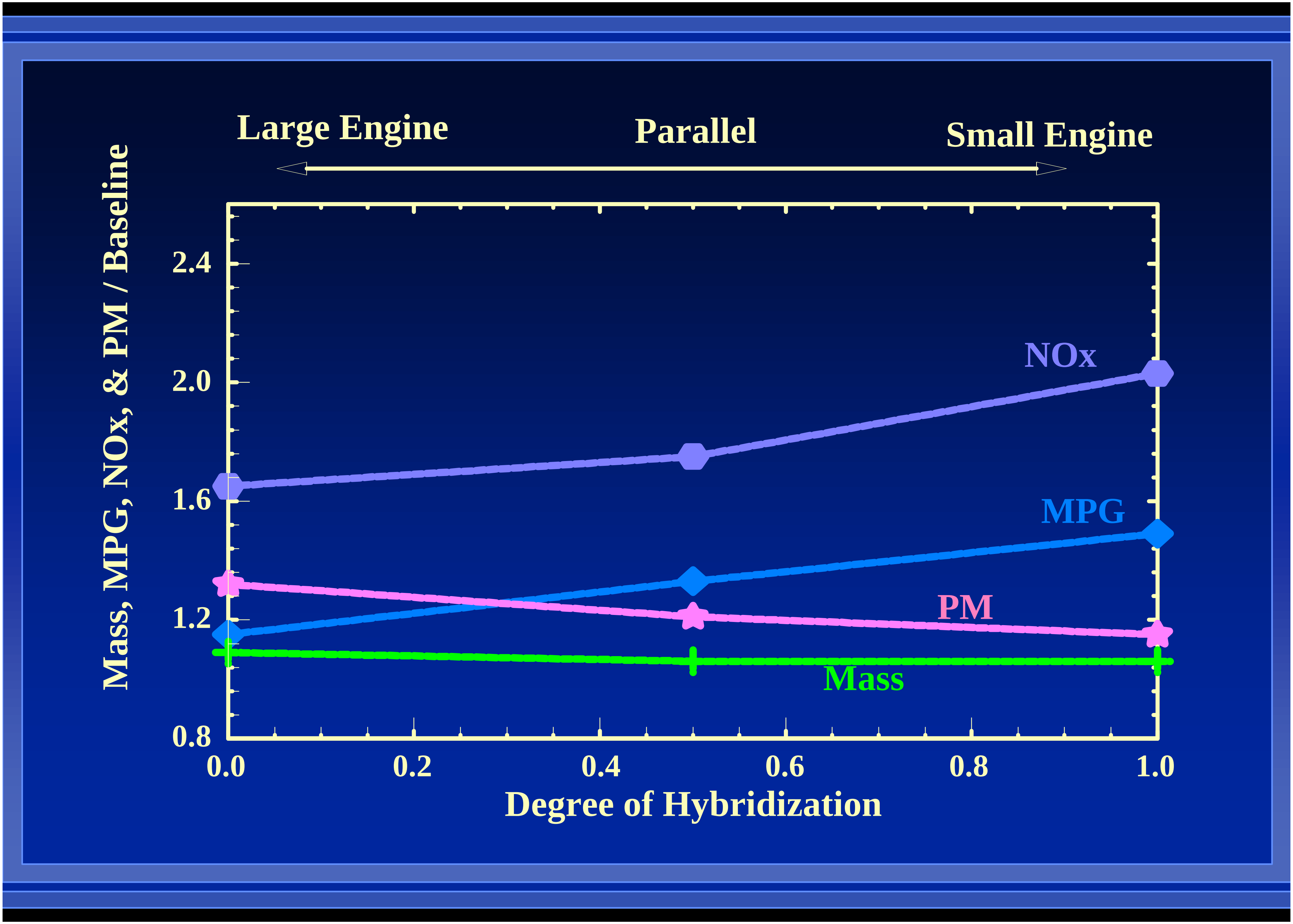
Parallel hybridization helps move operating points into higher efficiency regions



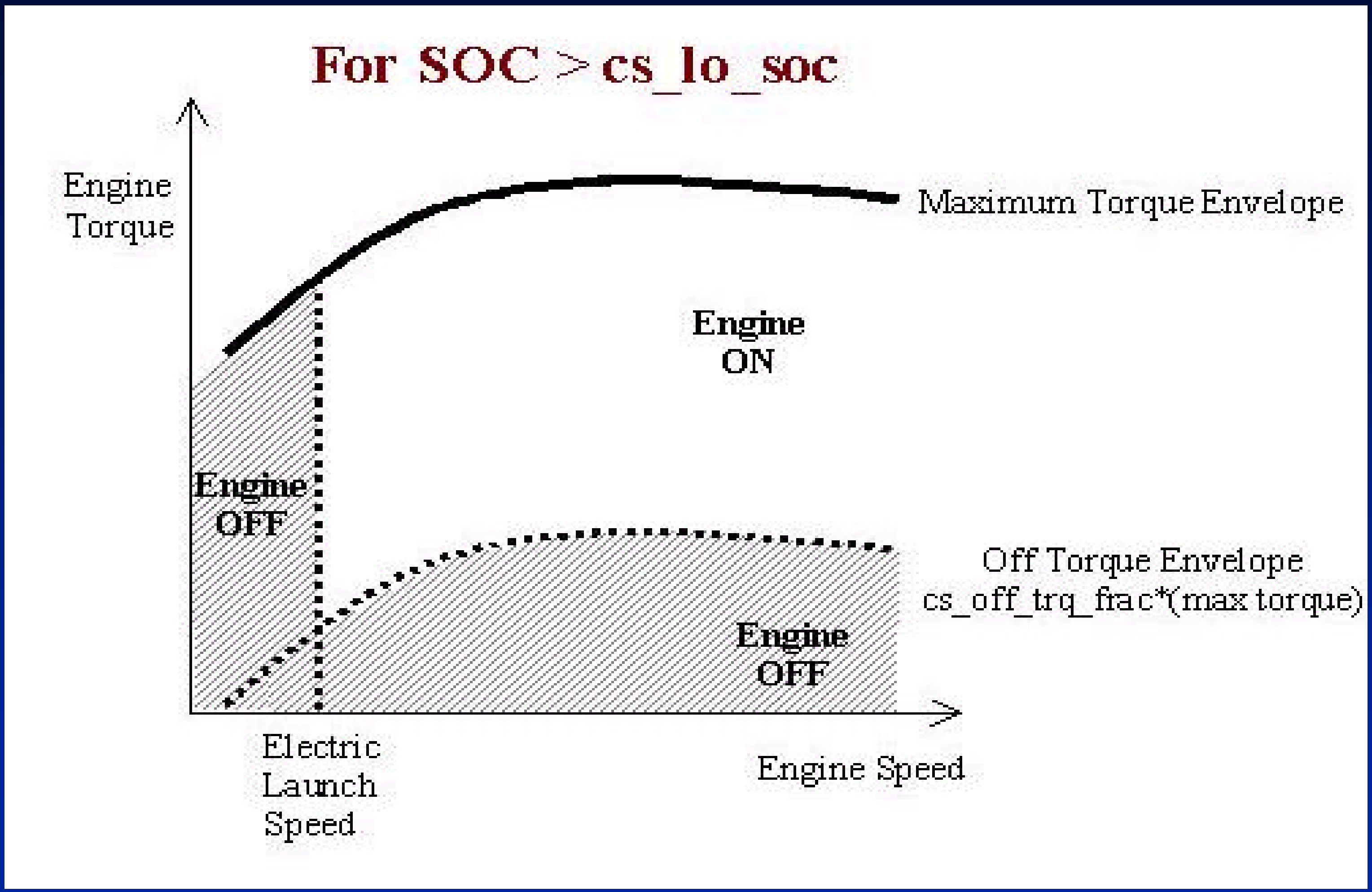


Degree of Hybridization: Definition

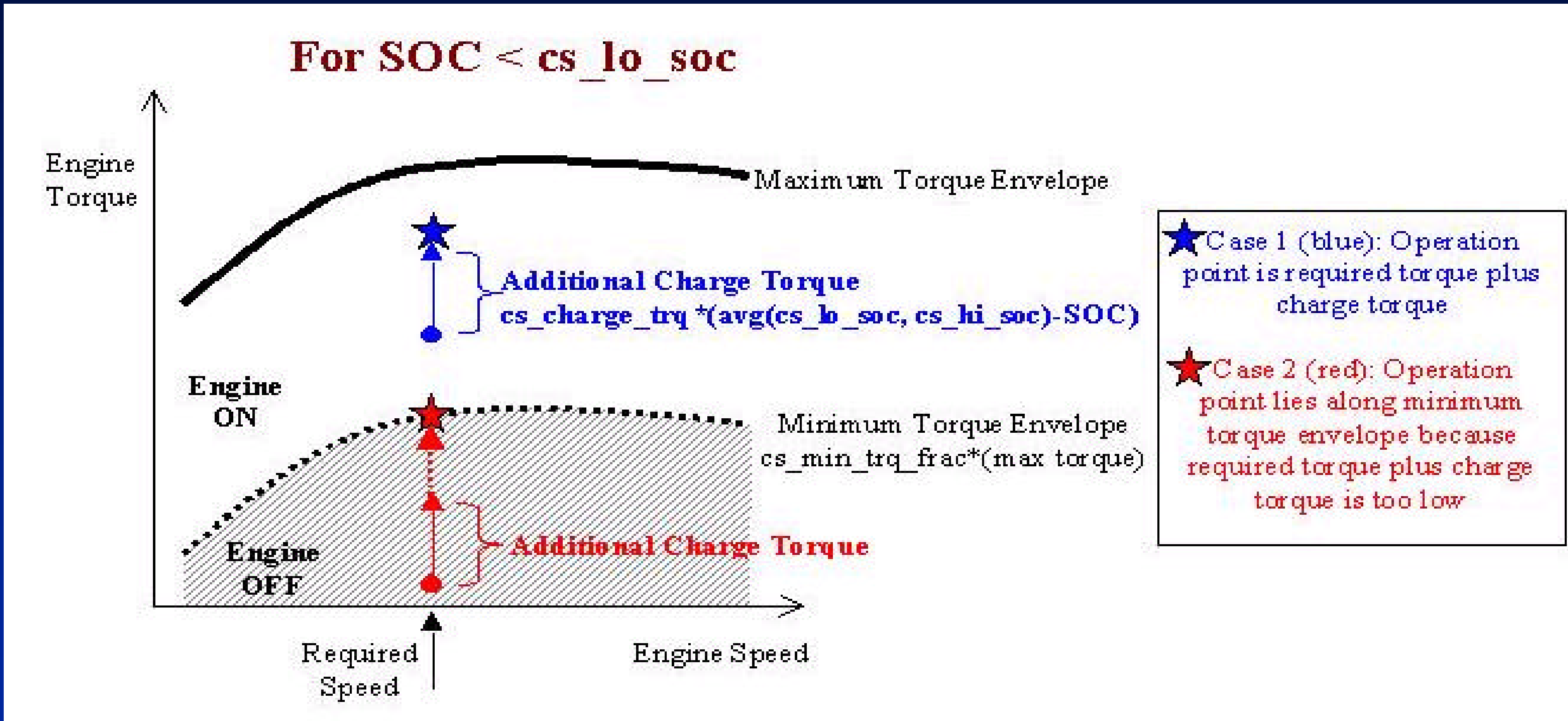



Large Engine
Parallel
Small Engine
NOx
MPG
PM
Mass
2.4
2.0
1.6
1.2
0.8
0.0
0.2
0.4
0.6
0.8
1.0
Degree of Hybridization
Mass, MPG, NOx, & PM / Baseline

Parallel HEV Control Strategy

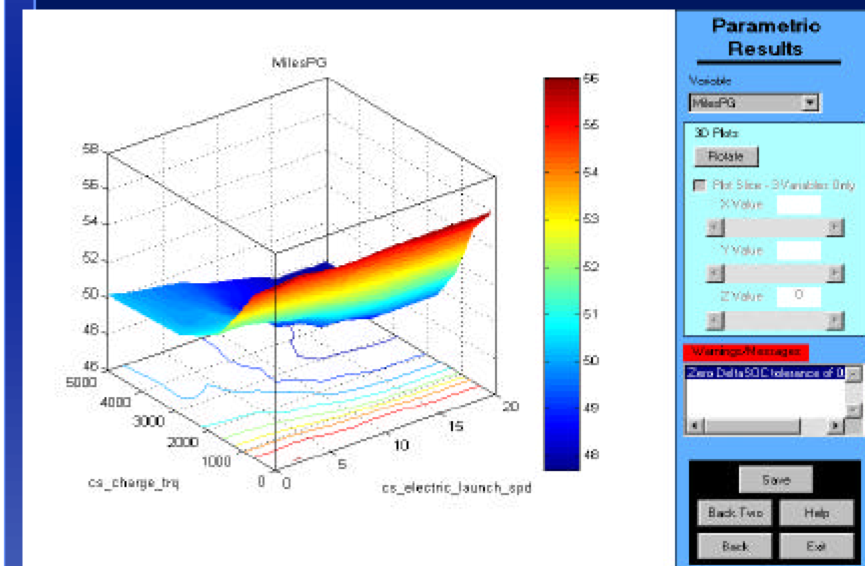


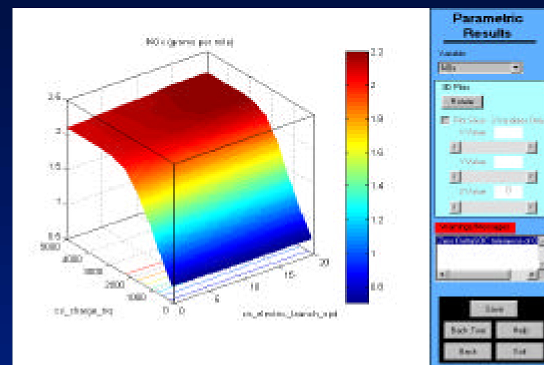
Parallel HEV Control Strategy

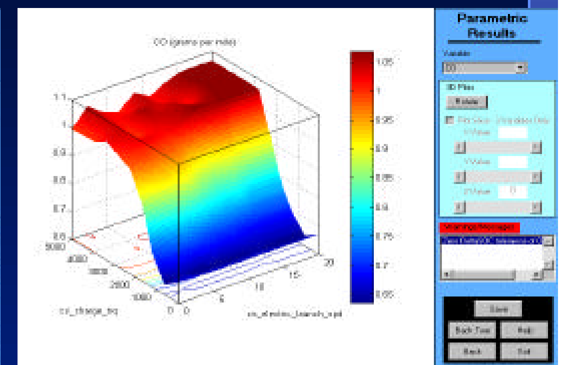


Trade-Offs Between Fuel Economy and Emissions Become Visible in Parametric Studies

Fuel Economy





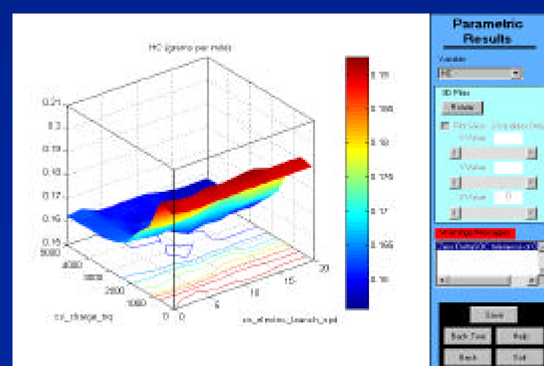


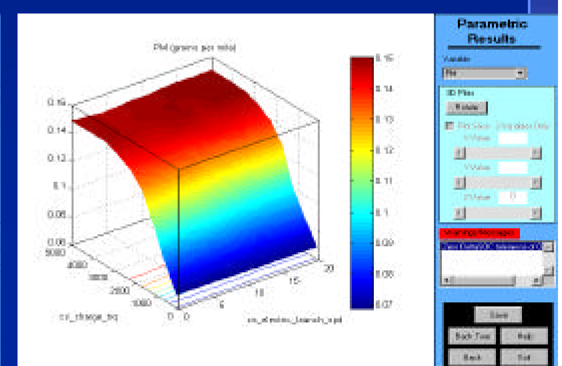
NOx

CO

HC

PM





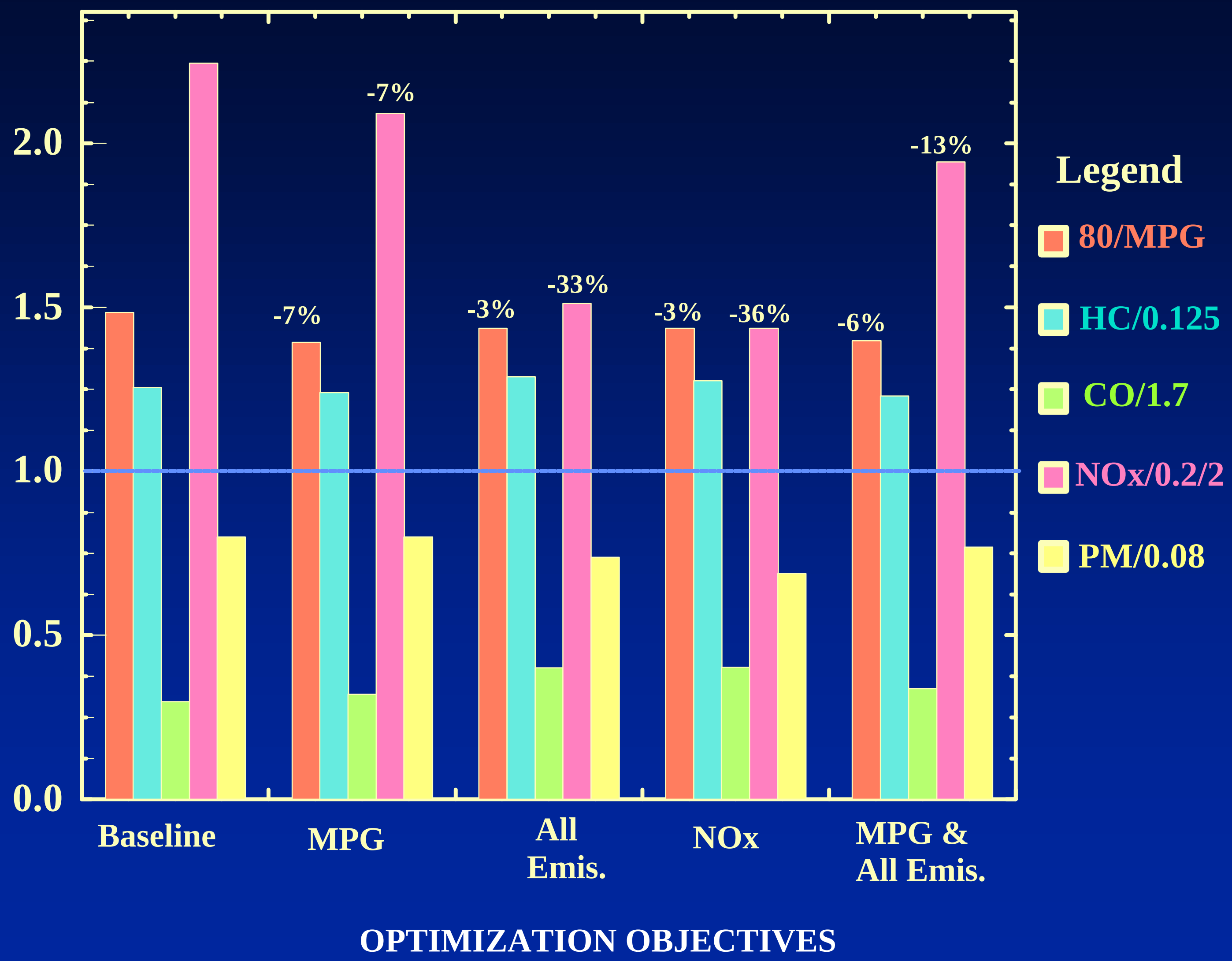
Full Optimization Allows Efficiency/Emissions Tradeoffs to be Performed Mathematically

- Goal: Balanced fuel economy and emissions
- Define an objective function that:
  - Includes emissions and fuel economy
  - Normalizes values to targets
  - Includes “tuning” parameters

For example, minimize :

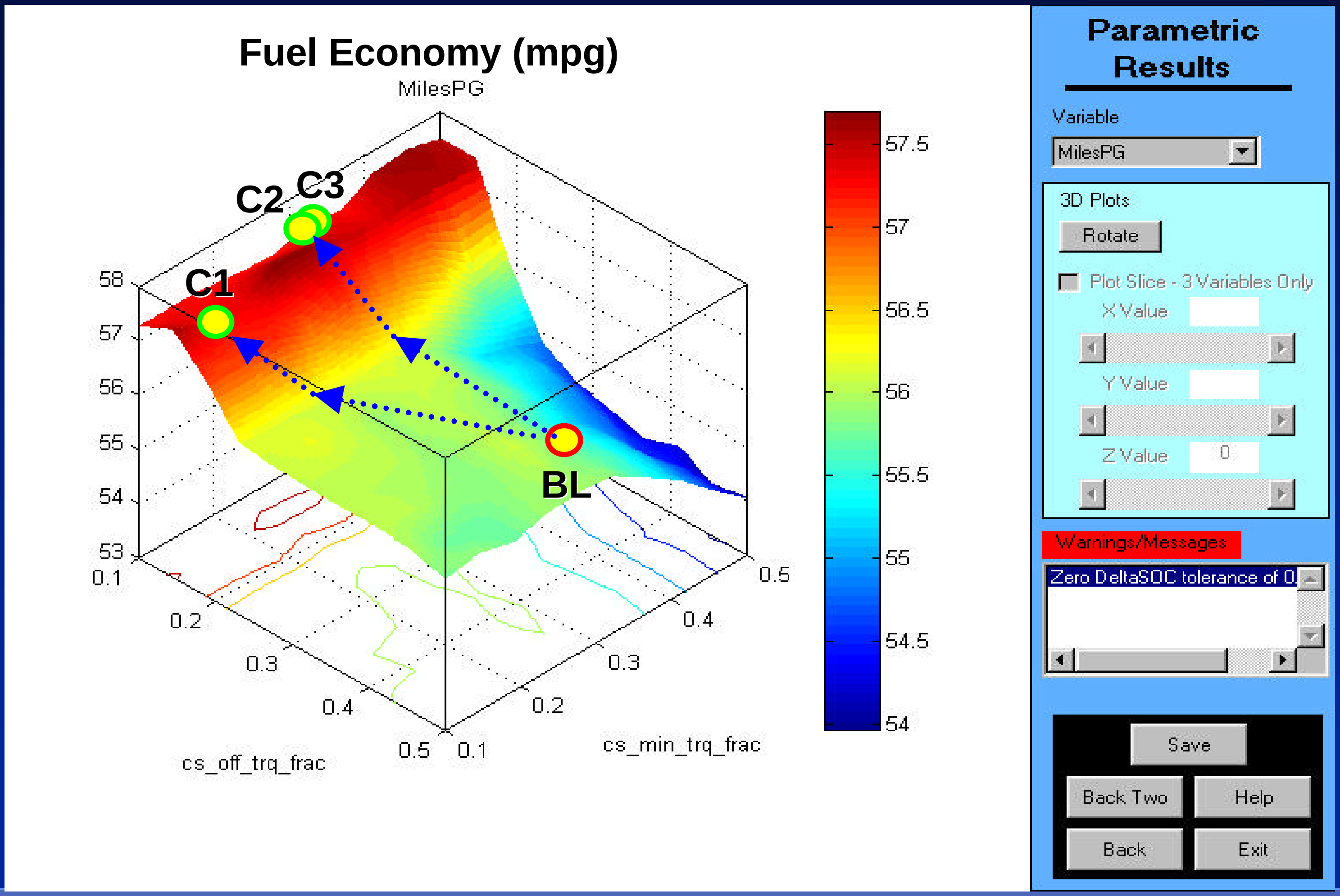
$$f = A\left(\frac{80\,mpg}{\text{fuel economy}}\right) + B\left(\frac{HC}{0.125}\right) + C\left(\frac{CO}{1.7}\right) + D\left(\frac{NOx}{0.2}\right) + E\left(\frac{PM}{0.08}\right)$$

Control Strategy Optimization: 0.5 Parallel HEV



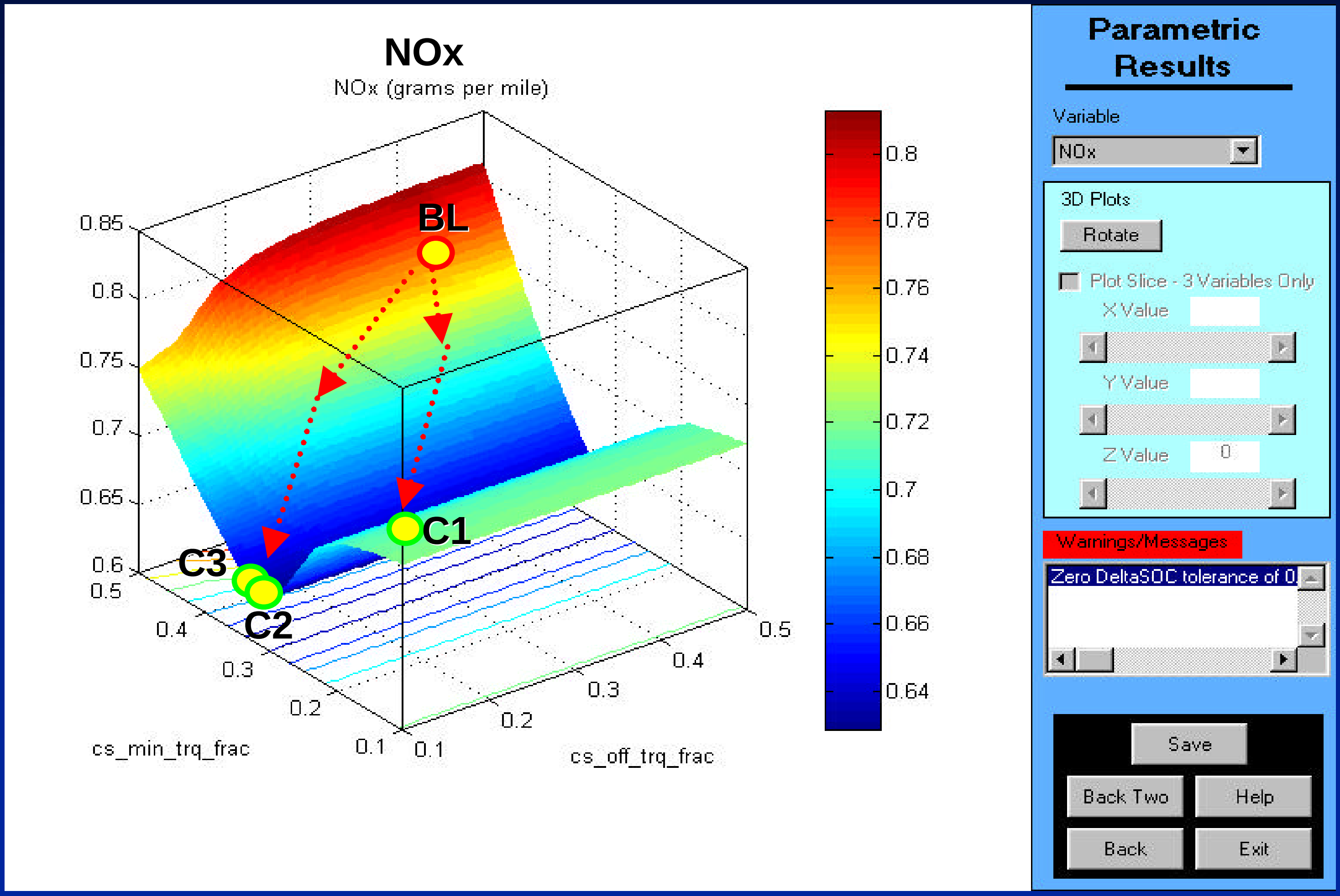
Moving from Baseline to Optimal Fuel Economy: Minimum-Torque and Off-Torque Fractions

(FE shown for FTP only, not FTP/hwy, Parametric Sweeps Performed Starting at Baseline)



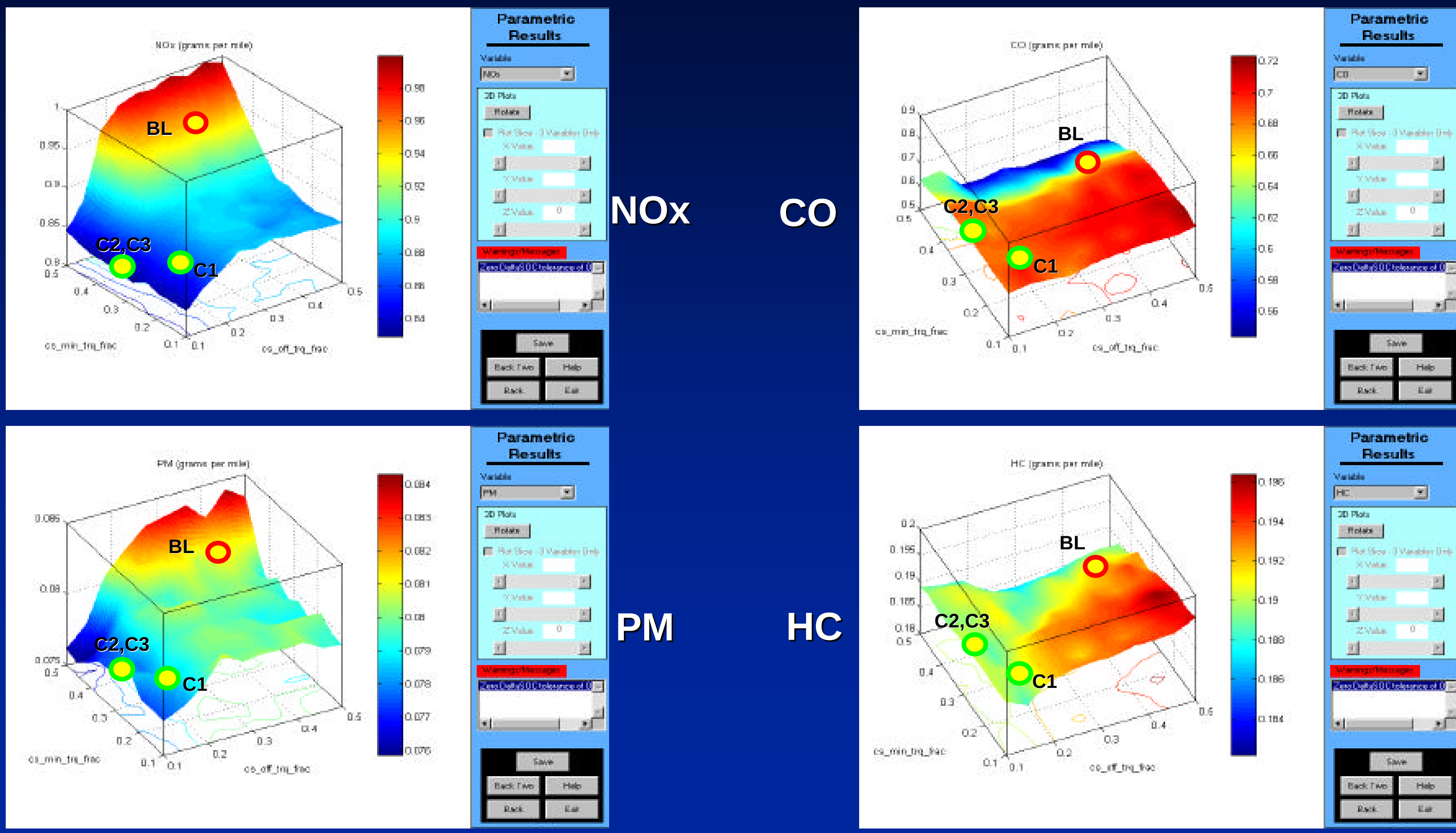
Moving from Baseline to Optimal Emissions: Minimum-Torque and Off-Torque Fractions

(Parametric Sweeps Performed Starting at Case 2)



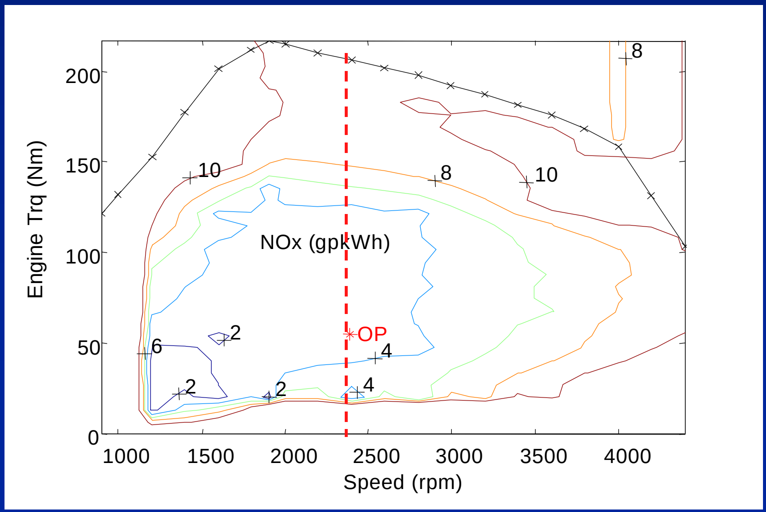
Effect of Charge-Torque and Off-Torque on Emissions Trade-offs: Better NOx, PM, But Worse CO, HC

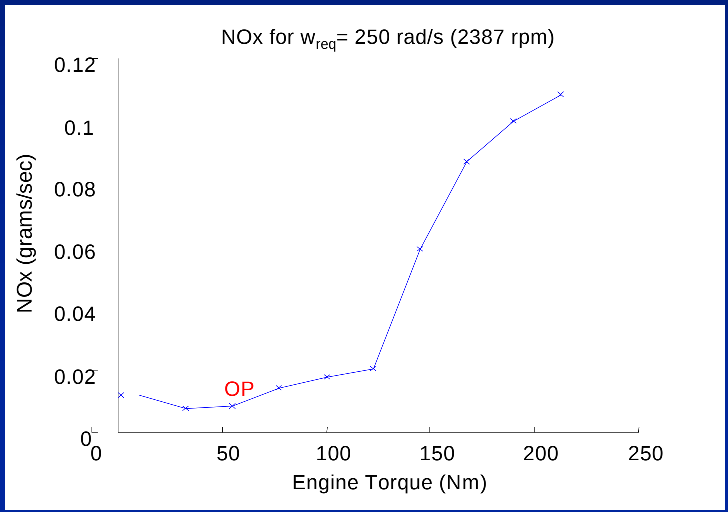
(Parametric Sweeps Performed Starting at Baseline)

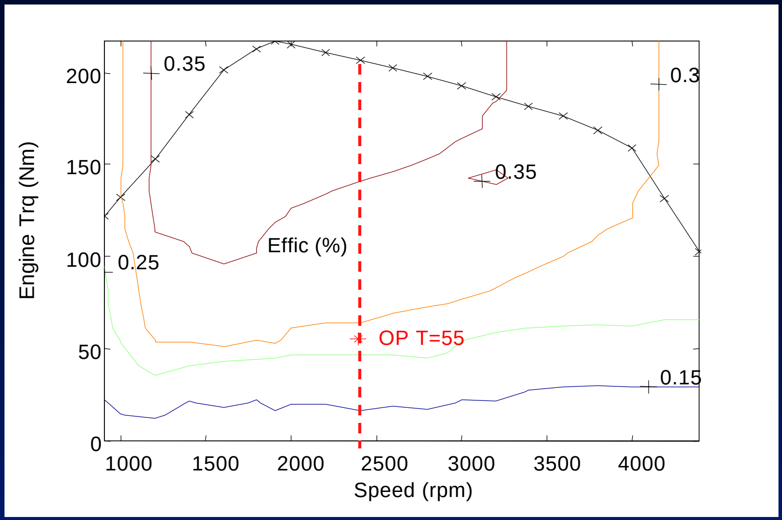


Control Strategy Development

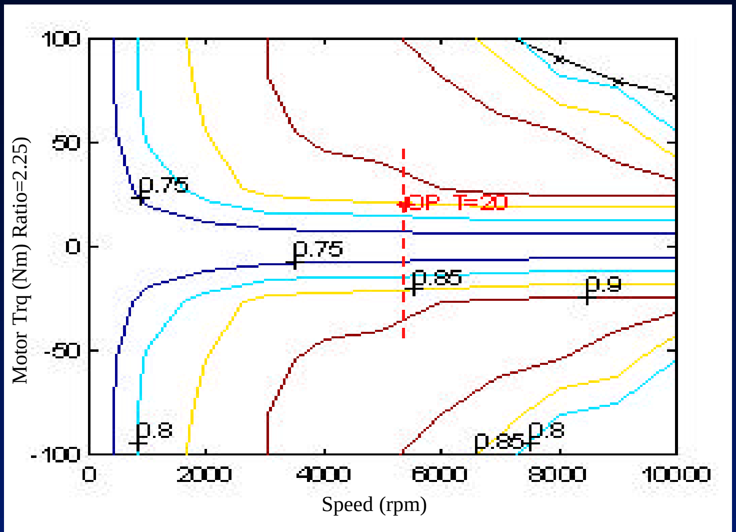
- Goal: minimize energy usage and emissions
- User can weight importance of mpg, HC, CO, NOx, & PM
- For each operation point (a given speed), look at range of possible engine-motor torque combinations
- Performance is weighted sum of instantaneous mpg & g/mi
- Transient thermal effects (engine & catalyst) are included





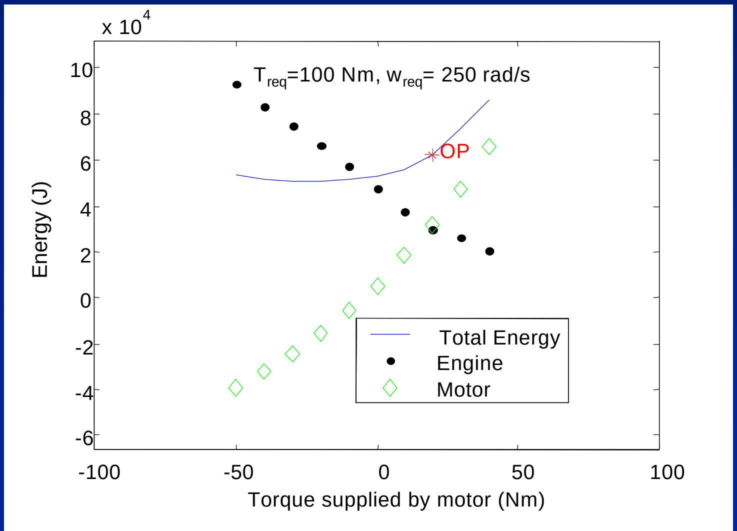


Engine Efficiency



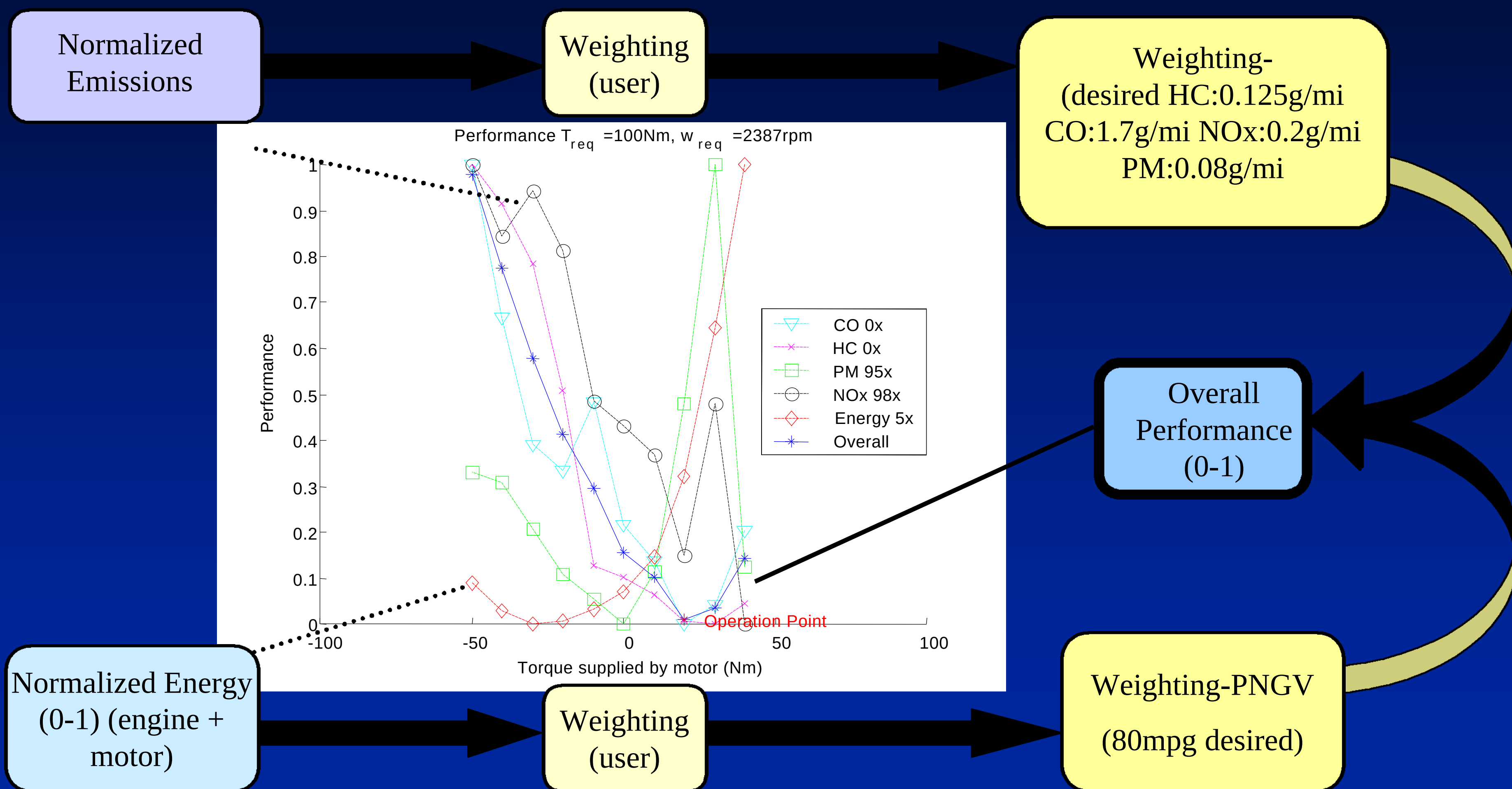
Motor Efficiency

- Energy used by engine from fuel
- Energy used by motor determined by an effective “cost” of using the motor and batteries (= energy to regain lost ΔSOC)

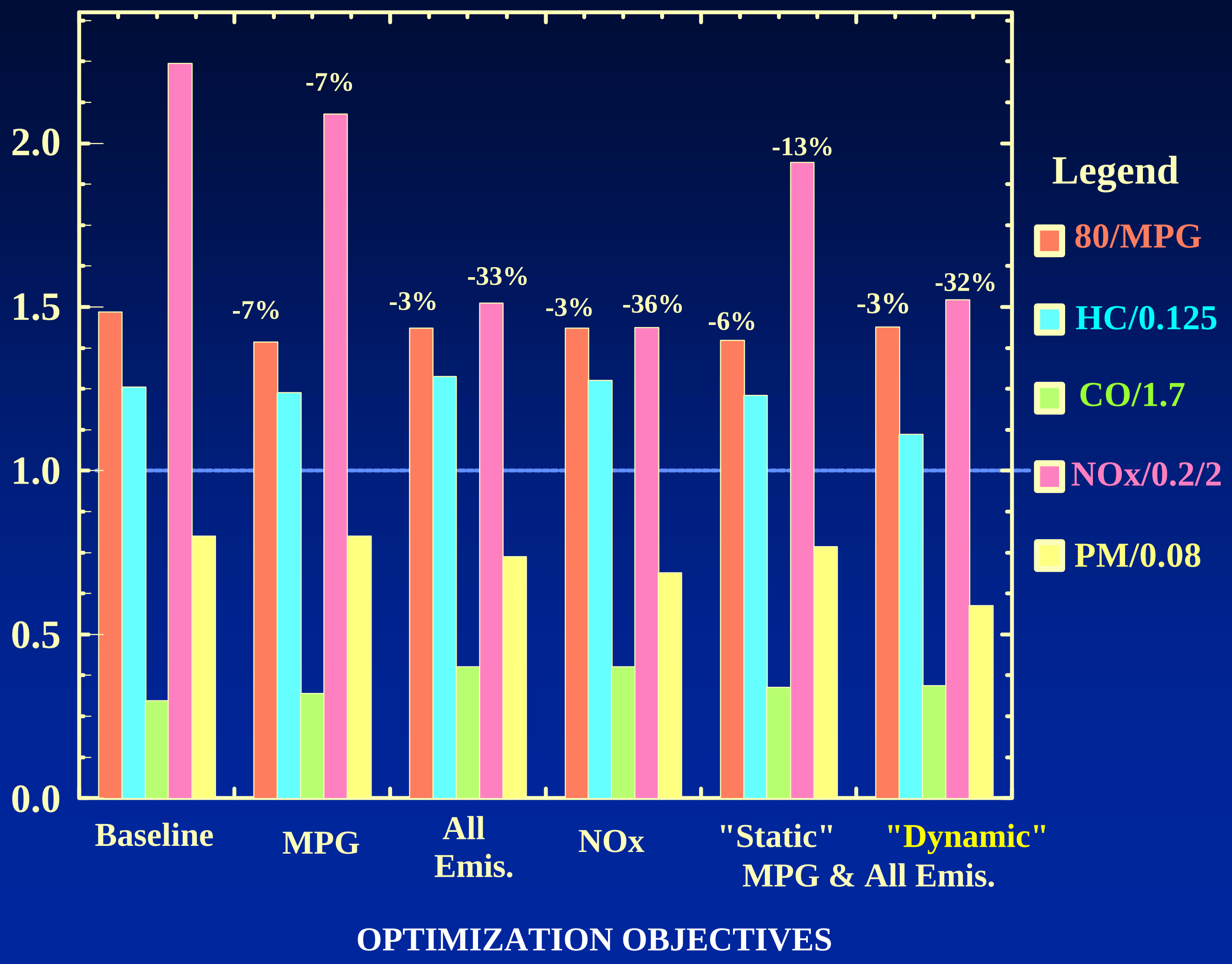


Energy Usage

Control Strategy: Performance Function



“Dynamic”Control Strategy: 0.5 Parallel HEV

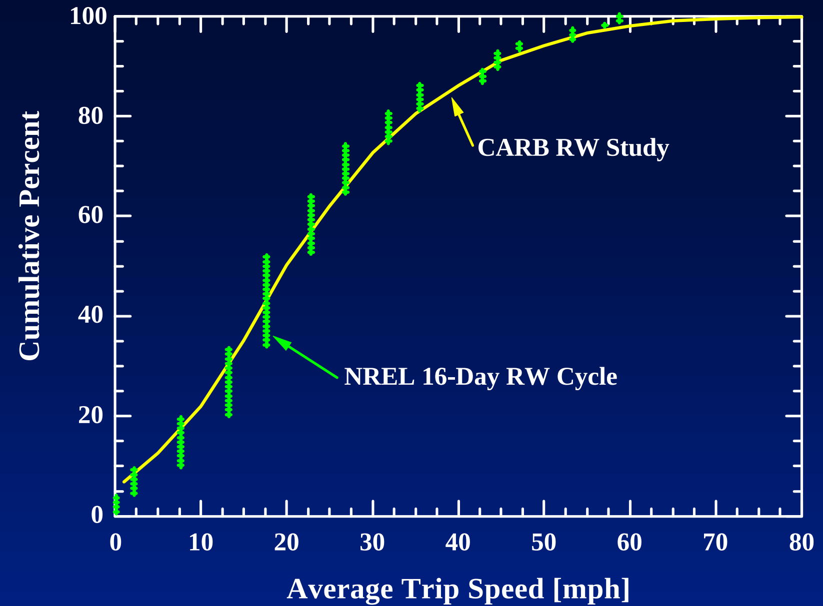


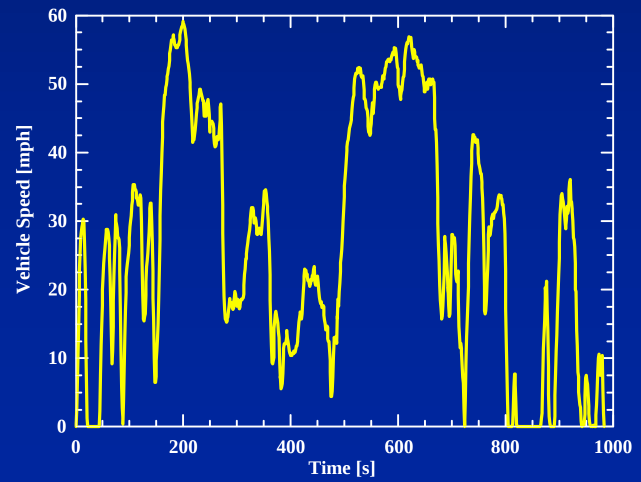
NREL 16-day “Real-World” Drive Cycle

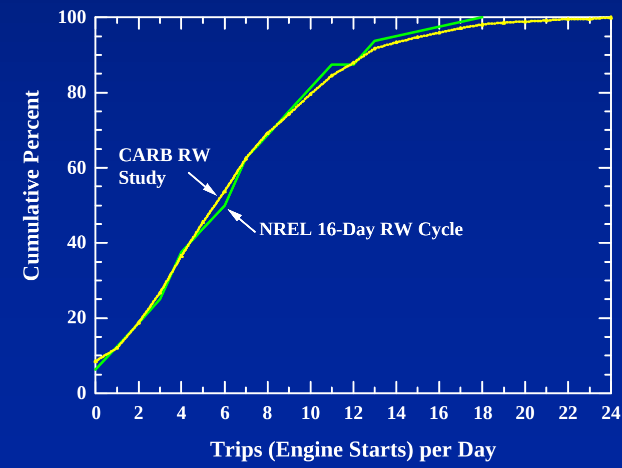
Table 5 - Summary of CARB Unified Correction Cycles

	Mean Speed (mph)	Max Speed (mph)	Max Accel (mph/s)	PKE* (ft/s^2)	Dis-tance (miles)	Stops/ Mile	Idle (%)	Accel (%)
UCC5	2.4	12.9	2.8	1.86	0.1	31.2	60.8	18.0
UCC10	8.0	28.0	4.1	1.74	0.8	8.5	44.5	27.2
UCC15	13.3	36.5	4.6	2.20	1.5	3.84	27.7	40.5
UCC20	17.7	43.8	5.7	1.92	4.1	3.16	16.1	42.3
UCC25	22.9	49.8	5.8	1.72	5.4	2.02	13.2	43.8
UCC30	26.8	59.1	5.4	1.41	7.3	1.36	8.8	45.5
UCC35	31.9	68.7	5.6	1.27	11.9	1.00	7.9	45.7
UCC40	35.6	72.3	5.5	1.11	13.1	0.68	5.6	47.1
UCC45	44.6	71.4	5.7	1.06	16.1	0.43	3.7	45.7
UCC50	43.2	71.6	5.8	0.73	26.1	0.31	6.6	47.5
UCC55	47.4	71.1	5.6	0.66	30.3	0.23	4.7	44.8
UCC60	53.8	70.7	5.9	0.74	41.7	0.19	3.7	43.4
UCC65	57.3	81.4	5.8	0.58	61.2	0.13	3.5	44.9
UCC70	59.1	83.0	6.1	0.71	59.7	0.10	2.0	46.5
UCC75	67.65	88.7	5.9	0.67	91.1	0.07	2.0	49.9

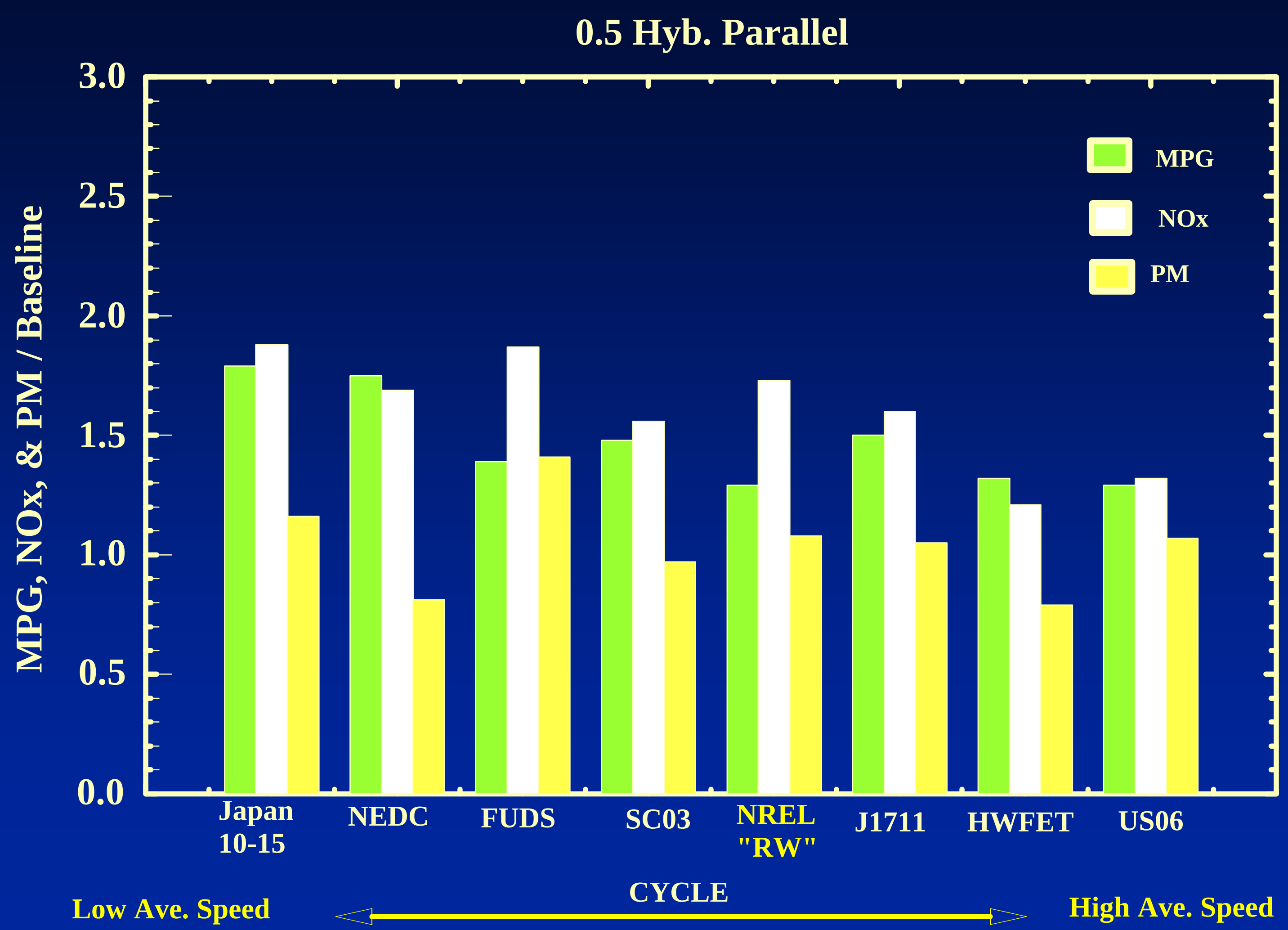
*PKE = Positive kinetic energy







Effect of Drive Cycle on Parallel Hybrid



Conclusions

- Hybrid vehicles provide additional vehicle and control optimization opportunities
- For the vehicle studied, increasing the “degree” of hybridization led to higher MPG (up to 1.5X) and lower PM, but also higher NOx (up to 2X)
- Parametric sweeps of control strategy parameters provide insight about trade-offs
- Numerical optimization becomes critical when number of design variables exceeds 2 or 3

Conclusions (cont'd)

- Control strategies can be designed to balance fuel economy and emissions
  - Case 1: 7% ↑ MPG, 7% ↓ NOx
  - Case 3: 3% ↑ MPG, 36% ↓ NOx
  - Case 4: 6% ↑ MPG, 13% ↓ NOx
- The drive cycle affects the relative merit of design selections: parallel HEVs show higher MPG but also higher NOx (w.r.t. conventional) on slower cycles